Spherical Cusp for High Energy Density Plasma Confinement

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Abstract - *In the majority of confinement configurations used to confine plasma, there is a tendency toward instability due to the fact that the corresponding magnetic field lines can shorten themselves causing a disruption. The exception, in terms of confinement configurations, is when the magnetic field lines curve away from the plasma, or in other words, when the confinement configuration is a magnetic cusp. This configuration is inherently stable due to the fact that an instability requires an expenditure of energy to stretch the lines of force to fill the volume previously occupied by the plasma. This concept involves the idea of suspending a small spherical cusp inside the core of a larger spherical cusp using a reverse field support structure along with the use of a gyrotron and a particle injector array to provide sufficient confinement time and magnetic insulation to create and maintain a high energy density plasma.*

Introduction - The spherical cusp is an innovative confinement concept that has the potential to create and maintain the densities and temperatures necessary for controlled fusion. This project involves the design and construction of a set of superconducting coils for installation inside a large diameter vacuum chamber. The coils will be designed in a spherical array with the coils extending away from the center in the radial direction. The motivation for the spherical cusp configuration is the potential for stable magnetic confinement of high energy density plasma.

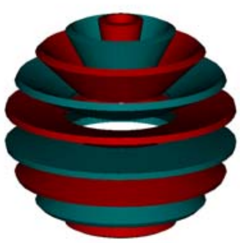

Figure 1

Figure 2

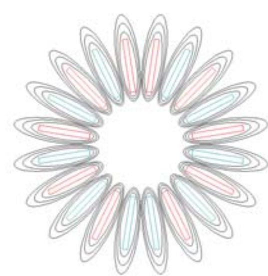

Figure 3

Figure 1 - This image shows the structure of the spherical cusp with each concentric layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.

Figure 2 - This image shows a cross section of the spherical cusp with each concentric layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.

Figure 3 - This image provides a rough sketch of the magnetic field for the spherical cusp with the magnetic field lines illustrating the magnetic contour as a result of positive and negative current flow in the blue and red coils.

Overview - The spherical cusp is an innovative confinement configuration designed to provide sufficient confinement time to maintain a high energy density population of particles in order to reach ignition conditions. This confinement configuration involves electron cyclotron resonance heating with the use of a pair of very high frequency (~200 GHz) gyrotrons along with a very strong magnetic field (~7.2 T) to operate in a regime that allows the microwaves to penetrate into the plasma with very little power loss. This operating regime, which is on the order of 5×10^{14} electrons per cubic centimeter, along with an ideal ignition temperature of 4 keV and 36 keV for D-T and D-D reactions, respectively, could produce breakeven conditions for steady state confinement times on the order of one second.

Figure 4

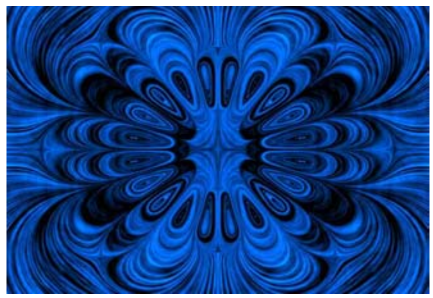

Figure 5

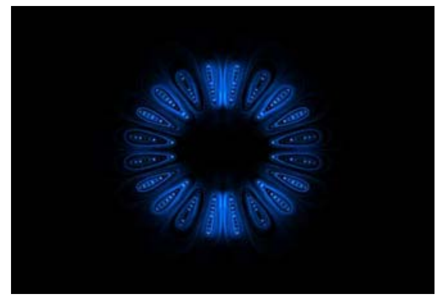

Figure 6

Figure 4 - This image shows the contour of the magnetic field for a spherical cusp with three concentric loops of current with each segment representing current in a direction opposite to the direction of each of the adjacent segments.

Figure 5 - This image shows the contour of the magnetic field for a spherical cusp with ten concentric loops of current with each segment representing current in a direction opposite to the direction of each of the adjacent segments.

Figure 6 - This image shows the strength of the magnetic field for a spherical cusp with ten concentric loops of current with each segment representing current in a direction opposite to the direction of each of the adjacent segments.

Confinement Stability - In the majority of configurations used to confine plasma, there is a tendency toward instability due to the fact that the corresponding magnetic field lines can shorten themselves causing a disruption. The exception, in terms of configurations, is when the magnetic field lines curve away from the plasma, or in other words, when the configuration is a cusp. This configuration is inherently stable due to the fact that an instability requires an expenditure of energy to stretch the lines of force to fill the volume previously occupied by the plasma.

Confinement Time - In experiments involving a magnetic cusp, sufficient energy confinement on the order of tens of milliseconds have been achieved, and where there was a large ratio of perpendicular to parallel velocity, hundreds of milliseconds have been achieved. For the case of $\beta \sim 1$, the confinement time is proportional to the magnetic field strength, the square of the radius and inversely proportional to the temperature, and with a radius on the order of 50 cm and a magnetic field strength on the order of 7.2 T, a confinement time on the order of one second can be achieved for very low temperatures. For temperatures on the order of 4 keV and 36 keV for D-T and D-D reactions, confinement times of 4.5 ms and 0.5 ms can be achieved.

Confinement Strategy - The strategy for improving confinement is based on five objectives: a significant reduction in charge exchange, a significant reduction in the loss of particles, a significant reduction in surface interactions, an efficient replacement of lost ions and electrons and an effective transfer of energy. Charge exchange can be reduced by maximizing the ionization fraction and minimizing the impurities in the plasma, particle losses can be reduced by increasing the radio of perpendicular to parallel velocities, surface interactions can be reduced by surrounding all surface structures with sufficient magnetic field insulation, the ions and electrons can be replaced by rapidly injecting large numbers for ions and electrons in symmetric packets of particles and the energy stored in the charged particles can be transferred to photons using a large reaction chamber and the interaction of charged particles with neutral gas particles.

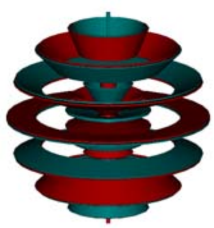

Figure 7

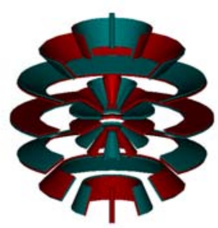

Figure 8

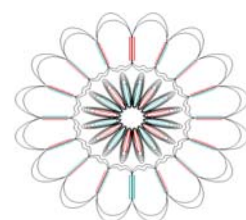

Figure 9

Figure 7 - This image shows the structure of two concentric spherical cusps with each layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.

Figure 8 - This image shows a cross section of the concentric spherical cusps with each layer representing a low resistance coil with the blue coils representing positive current flow and the red coils representing negative current flow.

Figure 9 - This image provides a rough sketch of the magnetic field for the two concentric spherical cusps with the magnetic field lines illustrating the contour based on positive and negative current flow in the blue and red coils.

Confinement Structure - The structure for sufficient confinement of a thermonuclear plasma in a spherical cusp involves the use of radial reverse field supports, concentric spherical cusps, electron cyclotron resonance heating, electron and ion particle injection and a very large chamber. In this configuration, the magnetic field coils are shaped in a conical form with radial reverse field support posts that extend from the outer portion of the coils with an inner spherical cusp that serves as the central plasma source and an outer spherical cusp that serves as a particle injector array. In addition, the particle densities are maintained or increased by injecting electron and ion packets using the particle injector array embedded inside the outer spherical cusp coils. These coils have a spacing of a few millimeters with a field of a few tesla and are capable of injecting more than ten times the number of particles lost from the inner spherical cusp.

Figure 10

Figure 11

Figure 12

Figure 10 - This image shows the structure of two concentric spherical cusps with reverse field support posts attached to each coil with the support posts designed to reverse the field to provide sufficient magnetic insulation.

Figure 11 - This image shows a cross section of the concentric spherical cusps with reverse field support posts attached to each coil with the support posts designed to reverse the field to provide sufficient magnetic insulation.

Figure 12 - This image shows the structure of a single magnetic cusp with a set of reverse field support posts attached to each coil to illustrate the structure of the support posts and the orientation of the reverse magnetic field.

Discussion - Energy demand is at an all time high, and if alternatives are not found in the very near future, world economies will decline. With a 3% growth in world energy consumption, the vast majority of the world's resources will be gone by 2050. The solution is fusion energy. This project will require an investment of $4,000,000 dollars leading to the development of a power system capable of producing energy at a rate of ten megawatts with electricity being produced at less than 1% of wholesale leading to annual revenue of more than $1,000,000 dollars per year.

Gyrotron Power	1 MW – 3 MW
Gyrotron Frequency	40 GHz – 240 GHz
Inner Magnetic Field	2 Tesla – 8 Tesla
Outer Magnetic Field	1 Tesla – 2 Tesla
Chamber Diameter	3 meter – 4 meter
Chamber Pressure	1 mTorr – 100 mTorr
Plasma Density	10^{14} cm^{-3} – 10^{15} cm^{-3}
Electron Temperature	1 keV – 100 keV
Injected Ion Energy	10 keV – 100 keV
Injected Electron Energy	1 keV – 100 keV

Acknowledgement - The images for figures 4, 5 and 6 were created by John Belcher at MIT.